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Software development for real-time ultrasonic mapping of tree canopy size

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Abstract

Ultrasonic transducers have been used for the digital control of agrochemical application rates in sprayers and fertilizer spreaders of tree crops for about 16 years. The early systems were developed before the advent of commercial DGPS receivers and relied on real-time tree canopy sensing and agrochemical rate adjustment according to the size of canopy detected. The widespread availability of fast and accurate DGPS service since 2000 and the rapid evolution of laptop computing power, has offered new opportunities for enhanced processing and spatial mapping of ultrasonically sensed orchard or grove data. The objective of this study was to develop and evaluate a Windows software application for a 10-transducer Durand-Wayland ultrasonic orchard measurement array and Trimble AgGPS132 DGPS that would allow real-time sensing, monitoring, calculation, storage and mapping of citrus tree canopy volume and height. Program code was written in Delphi 5.0 for Windows. Four main program windows displayed (1) real-time instrument status of ground speed, transducer outputs in a bar chart, canopy height, cross-sectional canopy area, and DGPS signal status; (2) database; (3) SQL filter pages to review and sort the acquired spatial data; and (4) canopy volumes and coordinates for individual trees in the citrus grove. The data collected with this automated system were compared with manually measured size data of 30 trees to estimate accuracy, and a grove of 376 citrus trees was surveyed twice with the system to estimate repeatability. Results showed no significant differences between ultrasonically and manually measured tree sizes ranging in height from 2.1 to 4.3 m ($R^2 = 0.940^{***}$; RMSE = 0.157 m) and in volume from 6.3 to 54.0 m^3 $tree^{-1}$ ($R^2 = 0.944^{***}$; RMSE = 3.14 m^3 $tree^{-1}$).

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The system located tree positions for GIS mapping purposes within 1.37 m, 95% of the time.

Keywords: DGPS; GIS; Transducers; Citrus; Precision agriculture

1. Introduction

Florida is the world's leading producer of grapefruit and second only to Brazil in orange production. The state produces over 80% of the United States' supply of citrus (Hodges et al., 2001). Considerable spatial variability of tree canopy sizes occurs in Florida groves, originating primarily from repeated tree resetting (planting young trees in vacant spaces of old groves), hedging/topping practice, variable tree spacing, and soil limitations. There is increasing interest by growers to manage these variable groves site-specifically using variable rate technology (VRT), potentially resulting in more efficient use of inputs, increased yields, and preventing environmental pollution by excess agrochemicals.

Ultrasonic transducers have been used for the digital control of agrochemical application rates in sprayers and fertilizer spreaders of tree crops for about 16 years (Roper, 1988). Giles et al. (1988) developed a system for electronic measurement of canopy volume. The system was based on ultrasonic range transducers mounted on an orchard air-blast sprayer. Ultrasonic transducers measured the distance to the canopy foliage and their performance was not affected by ground speeds of 2, 4 and 6 km h^{-1}. These early sensing systems were developed before the advent of commercial differentially corrected global positioning system (DGPS) receivers and relied on real-time tree canopy sensing and agrochemical rate adjustment according to the size of canopy detected. The widespread availability of fast and accurate DGPS service since 2000 and the rapid evolution of laptop computing power, has offered new opportunities for enhanced processing and spatial mapping of ultrasonically sensed orchard data. Kataoka et al. (2002) evaluated the performance of ultrasonic and laser beam transducers for crop height measurement. Ultrasonic transducers performed well for height measurement of soybeans and corn. Solanelles et al. (2002) compared a conventional sprayer with an air-assisted sprayer based on two ultrasonic transducers and solenoid valves for proportional application to the canopy volume. The arrangement could save 65 and 30% of spray liquid in olive and pear orchards, respectively.

Whitney et al. (2002) investigated the ultrasonic transducers' response to different parts of the citrus canopy and also examined the effect of sampling interval and transducer spacing on canopy volume determination. The correlation between ultrasonic and manually measured volumes of 60 trees ranging in size from 2 to 30 m^3 $tree^{-1}$ was affected more by decreasing the number of transducers than increasing the sampling interval along the row. The coefficient of determination for correlations between ultrasonically and manually measured canopy volumes ranged from 0.90 to 0.96. Root mean square errors (RMSEs) for the regressions ranged from 1.67 to 2.64 m^3 $tree^{-1}$. Tumbo et al. (2002) compared laser and ultrasonic measurements of citrus canopy volume with manual methods and found good agreement between all methods.

None of these previous studies used real-time data processing and instead, relied on laborious post-processing of collected data using spreadsheets in the laboratory. Li et al. (2002) and Zaman and Salyani (2004) used DGPS receivers for collecting tree location coordinates, but tractor speed was still estimated from stop-watch timers and canopy volumes were calculated by spreadsheet post-processing. A complete real-time tree canopy mapping system would use a DGPS receiver for tractor speed sensing and adjustment, and, together with position coordinates and ultrasonic ranging data, for the continuous calculation and storage of canopy sizes. Moreover, the performance of ultrasonic transducers should be continuously monitored during the measurement process, a function which was not possible during previous studies. Therefore, this study was designed to:

1. Develop a complete software interface solution for real-time ultrasonic measurement of tree size.
2. Design a graphical diagnostic software interface for the measurement system.
3. Evaluate the repeatability and accuracy of the software-controlled ultrasonic system to measure and map tree sizes in commercial groves.

2. Methods

2.1. Hardware for ultrasonic measurements

An ultrasonic ranging system (Durand-Wayland Inc., LaGrange, Ga.) was used in this study. The configuration used 10 ultrasonic transducers, numbered 1–10 from the ground up, and mounted at 0.6 m increments (D_S) on a 0.1 m diameter vertical PVC mast (Fig. 1). Transducer 1 was nominally 0.6 m above ground level, and transducer 10 was 6.0 m high. The mast was mounted on a custom trailer which was hitched behind a 4-wheel drive pickup truck, and driven at a speed of 1.0–1.5 m s^{-1} between two rows of trees so that the mast was approximately on the centerline (Figs. 1 and 2). In this configuration, each transducer would measure the horizontal distance (D_D) between the mast and the nearest peripheral foliage of the tree canopy (Fig. 1). A Trimble AgGPS-132 DGPS antenna (Trimble Navigation Limited, Sunnyvale, CA) was mounted at the mast between transducers 4 and 5 to collect horizontal position and ground speed data (Fig. 1). The DGPS receiver was configured for a 1 Hz acquisition rate using Coast Guard beacons for differential correction.

An on-board microcontroller and custom transducer-triggering circuitry (Durand-Wayland, 1998) controlled the rate of data acquisition from the 10 transducers. System design and other limitations such as the speed of sound (346 m s^{-1} in air at 25 °C) resulted in a complete 10-transducer scan rate of 5.1 Hz. The 10 transducers could not be triggered simultaneously due to possible inter-transducer interference, but were fired sequentially in four groups (Durand-Wayland, 1998). The total effective (return path) divergence angle of the ultrasonic pulse was about 12° (Li et al., 2002) at an operating frequency of 40 kHz. The maximum measuring range of the ultrasonic transducers was 7.6 m (Tumbo et al., 2002), and data were digitized in eight-bit format (0–255) so that 255 represented a distance of 7.6 m. The resulting distance resolution of each transducer was therefore 0.03 m. Data from the 10 ultrasonic transducers was transferred continuously to a 1.4 GHz laptop computer in the

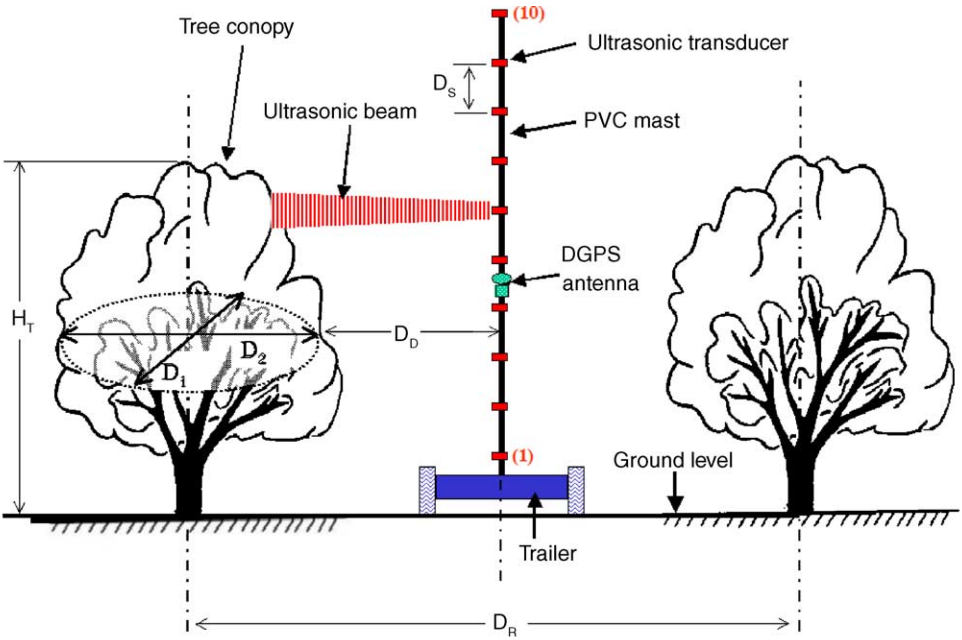

Fig. 1. Schematic layout of ultrasonic transducer system and manually measured tree dimensions used for calculation of tree canopy sizes in a citrus grove.

pickup truck's cab through a RS232 communication cable (9600,8,n,1), routed through the DGPS. The DGPS position data were simultaneously transmitted (merged) to the same laptop RS232 port at 1 Hz, using the National Marine Electronics Association (NMEA-0183) standard RMC sentence.

2.2. Software interface

The custom software for reading DGPS and ultrasonic transducer output, calculating tree canopy sizes, and storing the data in a central database was written in Delphi 5.0 (Borland Software Corp., Scotts Valley, CA) for a 32-bit Windows operating system (Microsoft Corp., Redmond, WA). The software incorporated configuration, setup and monitoring features on the main data collection page, to select the computer hardware, and to diagnose the correct operation of the ultrasonic transducer array and DGPS (Fig. 3). Each ultrasonic transducer's raw distance ranging output was continuously plotted in a horizontal bar chart, to represent a scale-model of the mast and ultrasonic array (Fig. 3). Real-time on-screen updates of ground speed were used to manually adjust the vehicle's speed to the target speed, and the cross-sectional area and height of the measured canopy were also displayed in real-time at 1 Hz (Fig. 3).

Incoming text strings of DGPS and ultrasonic transducer data were separated, parsed, and saved in program arrays before further processing. Every second (1 Hz), the DGPS coordinates from the previous and the current DGPS output were converted to decimal degrees,

Fig. 2. Vehicle and trailer with vertical array of 10 ultrasonic transducers and DGPS used to measure tree heights and volumes. Transducers are mounted from 0.6 to 6.0 m above the ground.

averaged, offset and saved to a MS-Access (Microsoft Corp., Redmond, WA) database table. A distance offset equal to one half row spacing was applied to each position coordinate pair so that the mapped canopy position was correctly placed on the tree row. The distance offset was calculated with Universal Transverse Mercator (UTM) projected coordinates by utilizing the ProLat UTM (Effective Objects, Issaquah, WA) program function. The UTM projection was selected because it produces a flat grid of geometrically correct cartesian ground coordinates in meters. Offset distance and direction data were obtained from the program's user interface (row width and row direction; Fig. 3). Corresponding ultrasonic range data (D_D) for the same time interval were averaged ($\bar{D}_{Di}$; Eq. (1) and used in Eq. (1) to calculate the average cross-sectional area of the tree canopy (A_C) perpendicular to the row direction.

$$A_C = 2\sum_{i=1}^{i=10}(0.5D_R - \bar{D}_{Di})D_S \tag{1}$$

where A_C: cross-sectional canopy area (m^2); D_R: tree row spacing (m); $\bar{D}_{Di}$: ith mean distance (averaged for 1 s) measured from the ith ultrasonic transducer to the tree canopy foliage (m); D_S: distance between ultrasonic transducers (m).

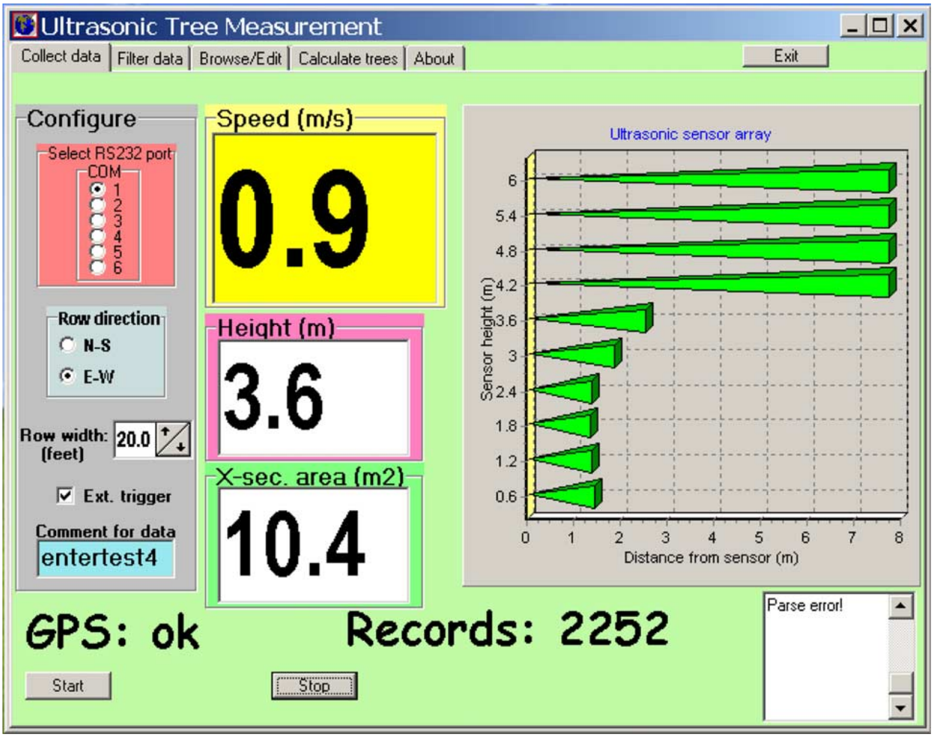

Fig. 3. Windows software user interface showing controls, ground speed, transducer diagnostics, and real-time tree size data.

Ultrasonic transducer distance measurements exceeding one half of the row width were eliminated from the calculation with an "IF" logic statement in the program. Because only one half of the canopy cross section was measured directly, the result was multiplied by two to represent the complete canopy, assuming approximate symmetry. Eq. (1) forms the sum of 10 rectangular areas defining the average cross-sectional shape of the canopy every second. Each rectangle is the product of canopy radius perpendicular to the row direction and transducer spacing for the *i*th transducer. Canopy cross-sectional area was saved to the MS-Access database every second, together with the 10 raw ultrasonic ranging measurements and date and time stamps corresponding to the DGPS measurements. The ground speed (in knots) was parsed from the DGPS string and converted to metric units, using speed ($\mathrm{m\,s^{-1}}$) = 0.51444 × speed (knots). Ground speed was also averaged for every adjacent coordinate pair, and saved to a MS-Access database table.

Average tree canopy heights were calculated at 1 s intervals by scanning all data arrays of 10 raw ultrasonic ranging measurements collected in each 1 s interval. The scan was conducted in a program loop from the top transducer (10) downwards to search for the first detected tree canopy within a ranging distance of half a row spacing. The tree canopy height for that completed ultrasonic scan was therefore approximately the midpoint between the

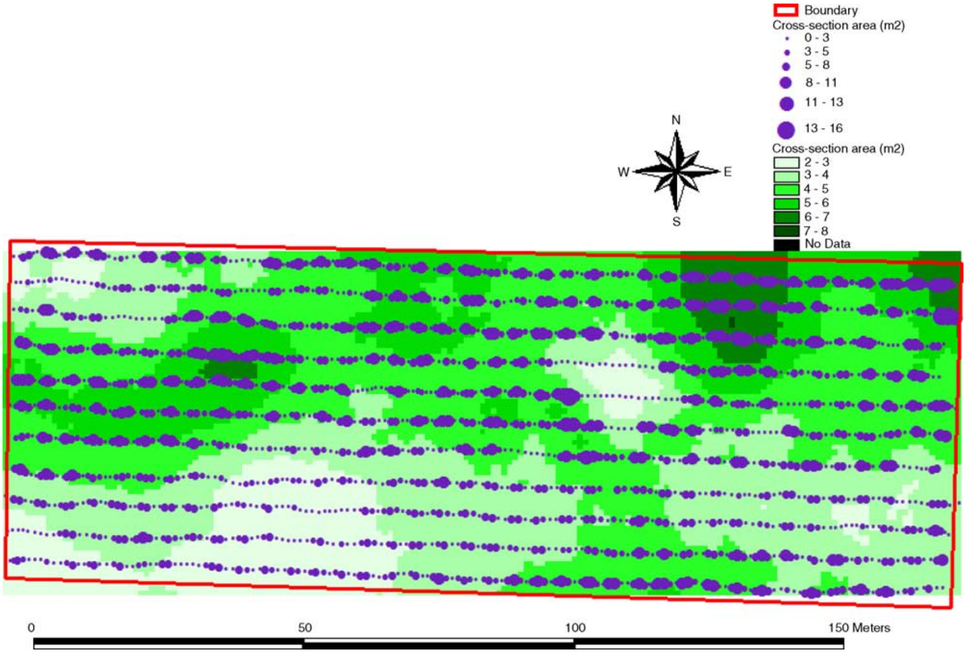

Fig. 4. GIS map of cross-sectional canopy area calculated by ultrasonic sensing of 11 tree rows (solid circles). Interpolated canopy area values are shown as shaded zones.

height of the first transducer from the top of the mast to detect the canopy, and the one above it. By averaging the canopy heights of individual scans completed in 1 s, a smoothed tree canopy height was calculated and saved in the database.

The database table could be easily viewed and filtered in the “browse/edit” and “filter data” pages of the program (Fig. 3). Cross-sectional areas and heights of tree canopy, together with matching coordinates could then be viewed and easily exported by copying to the Windows clipboard, and pasting to a spreadsheet or GIS program for further processing or mapping. Arcview 3.2 (ESRI, Redlands, CA) was used to map the individual averaged tree canopy data and the interpolated canopy size surface was obtained with its “neighborhood statistics” analysis function (Fig. 4).

The canopy volumes of individual trees were calculated in either of two methods, depending on the grove condition. The first method was semi-automated in Arcview. We generated a regular grid of tree spaces for every tree in the grove using the Arcview extension “Orchard” (Lincoln Ventures Ltd., Hamilton, NZ) and ground truth measurements of tree spacing and grove dimensions. The sum of products of cross-sectional canopy areas and corresponding ground speeds for each tree space were then readily computed with the “summarize zones” function in Arcview, according to Eq. (2), with $t = 1$ s (1 Hz).

$$V_{TC} = \sum_{i=1}^{i=n} t S_i A_{Ci} \quad (2)$$

where V_{TC}: canopy volume for a single tree (m^3 tree^{-1}); n: number of complete averaged scans per tree (tree^{-1}); t: time interval for one complete averaged scan (s); S_i: ground speed at the ith averaged scan (m s^{-1}); A_{Ci}: ith cross-sectional tree canopy area (m^2).

The resulting sum represented canopy volume in cubic meters per tree space. Tree height was simply the maximum measured canopy height found in a tree space, and was also generated by the "summarize zones" function in Arcview. This semi-automated method using Arcview is applicable for grove canopies with strongly developed overlapping between trees (hedgerows) as well as groves with distinctly separate tree canopies.

The second method used an automated procedure developed in the "calculate trees" page of the custom program (Fig. 3) and was not intended for hedgerow groves because it relied on automatic location of the tree positions. The method used a search algorithm to sequentially scan the cross-sectional canopy area data for the beginning and end points of single tree canopies. Minimum values defined the canopy boundaries (usually zero), and maxima indicated the location of the tree trunks. After each sequence of data in the database was identified as belonging to a tree, the tree volumes could be computed using Eq. (2). Heights were simply the maximum height values for each selected sequence, and the tree position coordinates were the same as the coordinates of the maximum height values (trunk positions). These tree height, canopy volume and position coordinate values were saved to a separate table in the database.

2.3. Real-time performance tests and data analysis

The performance of the new software and ultrasonic system was assessed by surveying the tree canopy sizes in a number of different citrus groves. For this study, a small bearing 'Hamlin' orange (*Citrus sinensis* [L.] Osb.) grove of 1.18 ha size, located at the Citrus Research and Education Center (28°6.3′N; 81°42.9′W) in Polk County, Florida, was selected for testing the accuracy and repeatability of the ultrasonic measurements. The rootstocks for the trees were Swingle citrumelo (*Citrus paradisi* Macf. × *Poncirus trifoliata* [L.] Raf.). The planted tree spacing was 6.1 m (between rows) × 4.6 m (within rows) and most tree canopies were still separate because the trees were not fully grown. Two independent ultrasonic survey replicates (R1, R2) were conducted on the same 11 tree rows, using the same route, during 28 May 2003 and 30 May 2003, respectively. Actual ground speed, monitored on the main software screen during the surveys (Fig. 3), was maintained at about 1.0 m s^{-1}. The 11 rows contained 423 tree spaces, in which the ultrasonic system found 397 and 396 living trees during R1 and R2, respectively. The trees on the end of each row were excluded from the analysis to eliminate speed and position errors incurred while the vehicle was turned at the row ends. The final data set for each replication was therefore reduced to 376 trees. In order to assess the accuracy of ultrasonically measured tree canopy size, these data were correlated with manually measured tree size parameters on 30 randomly selected trees in the same grove. The following formula was used for manually calculating the single tree canopy volumes (Eq. (3); Fig. 1). The formula is based on one- half an ellipsoid and has also been used in other studies (Wheaton et al., 1995; Tumbo et al., 2002).

$$V_M = \frac{\pi}{4} D_1 D_2 H_T \left[1 - \left\{ \frac{1 - (H_i/H_T)^2}{3} \right\} \right] \tag{3}$$

where V_M: manually measured canopy volume (m^3 tree^{-1}); H_T: tree canopy height above ground level (m); H_i: height of intercept between two adjacent trees (m); D_1: maximum canopy diameter parallel to row (m); D_2: maximum canopy diameter perpendicular to row (m).

The repeatability of ultrasonically measured tree canopy size was estimated by correlating the two replications of all 376 tree sizes, as well as the 30-tree subset, using linear regression analysis (Genstat 6.0, Oxford, UK). For both accuracy and repeatability regressions, the coefficient of determination (R^2) and root mean square error (RMSE) were used to assess the goodness of fit. Student's two-sided *t*-test was used to test whether the two replications of manually measured tree size variables were significantly different from each other, or significantly different from the ultrasonically measured variables, and whether the two replications of ultrasonically measured variables were significantly different.

The repeatability of the tree position data was affected by many factors, including the performances of the DGPS and the automated tree volume calculation algorithm. We calculated the positional error of the 376 trees in R1 and R2 by calculating the Euclidean distance between corresponding tree positions in separate surveys. The mean, median, minimum, maximum, and 95-percentile were calculated for these distances to estimate the overall repeatability of the complete DGPS-software-vehicle system.

3. Results and discussion

3.1. Software performance and data mapping

The software interface performed reliably during these surveys, permitting the real-time measurement, calculation, presentation and storage of tree canopy size data. The software permitted accelerated processing of ultrasonic data; many previous studies had involved collection of serial port data to a text file during the survey, followed by laborious manual post-processing (parsing, sorting, calculating) of data in spreadsheets. This new software interface required no post-processing of data. The graphical user interface allowed monitoring of speed, ultrasonic transducer and DGPS function during a survey, so that errors could be quickly identified and corrected.

Average actual ground speeds during the surveys were $1.12 \pm 0.11\,m\,s^{-1}$ and $1.10 \pm 0.09\,m\,s^{-1}$ for R1 and R2, respectively. Each survey took about 29 min to complete, and collected 1740 ultrasonic canopy size measurements. Individual tree canopies could be discerned from a map of all measured canopy cross-sectional areas (A_C; Fig. 4), where the size of the plotted point was proportional to the cross-sectional area. Gaps between canopies and missing trees were represented by the smallest range (0–3 m^2). A smoothed map of cross-sectional canopy areas, developed by interpolation of individual measured points, identified contiguous classified zones of the grove where tree sizes were different (Fig. 4). The locations of these spatially variable tree growth differences were easily identified on the ground from the map, and further investigations could be conducted to determine the reasons. Cumulative cross-sectional canopy areas could be calculated easily with Arcview, either for the entire measured grove area, or for predefined sub-plots in the grove. The sub-plots need only be created as GPS coordinates on the ground, and GIS polygons on the

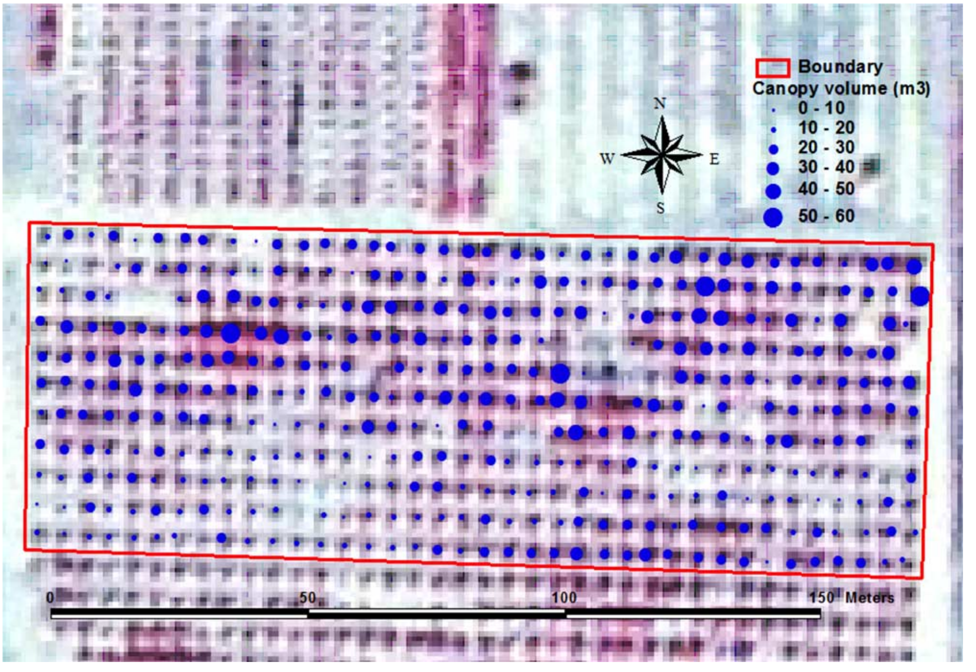

Fig. 5. GIS map of individual tree canopy volumes calculated by ultrasonic sensing of 11 tree rows (solid circles). The base map is a color-infrared aerial photograph of the grove, taken in 1999.

computer, thus allowing rapid assessment of tree growth in experiment plots or monitored zones of the grove.

Individual tree canopy volumes (V_{TC}) were calculated by the automated tree locating subroutine and corresponded well when overlaid with the 1999 aerial photograph of the grove (Fig. 5). The automated method was well suited to these trees because the tree canopies within rows had not yet merged. There are a few trees visible on the aerial photograph that were not shown on the tree canopy volume map (Fig. 5). These omissions were due to the 4-year age difference between the photograph and the ultrasonic measurements, specifically where some trees had been removed after 1999. The ultrasonically measured canopy heights and volumes of trees in the grove ranged from 0.9 to 4.5 m and 0.33 to 58 m^3 $tree^{-1}$, respectively (Table 1; Fig. 5). Individual trees with different performance characteristics or ages, and missing tree spaces, can be readily located from the ultrasonically measured grove map (Fig. 5). Cumulative canopy volume for the grove or for predefined sub-plots could be calculated with Arcview, and smoothed canopy volume or height maps could be generated with Arcview for the visualization of contiguous canopy size zones.

3.2. Repeatability and accuracy of ultrasonic measurements

Manually measured tree volumes and heights of the 30 selected trees ranged from 6.3 to 54.0 m^3 $tree^{-1}$ and 2.09 to 4.32 m, respectively (Table 1). The repeatability of manual

Table 1
Summary tree height and volume statistics for determining the repeatability of two ultrasonic and manual measurement replications (R1, R2) and the accuracy of the ultrasonic measurements (UH, UV) relative to the manual reference measurements (MH, MV) of 30 selected trees in a small grove of 376 trees

	n	Mean	Maximum	Minimum	R^2	RMSE	*t*(d.f.) *F*-probability
MVR1 (m^3 tree^{-1})	30	26.36	54.69	6.31	0.995^{***}	0.868	0.10 (58)
MVR2 (m^3 tree^{-1})	30	26.02	53.34	6.33			0.918 NS
MHR1 (m)	30	3.18	4.35	2.10	0.996^{***}	0.0397	0.10 (58)
MHR2 (m)	30	3.16	4.29	2.07			0.923 NS
UVR1 (m^3 tree^{-1})	30	22.87	52.05	3.06	0.945^{***}	3.14	−0.44 (58)
UVR2 (m^3 tree^{-1})	30	24.37	52.82	4.23			0.660 NS
UHR1 (m)	30	3.22	4.50	2.10	0.929^{***}	0.170	−0.12 (58)
UHR2 (m)	30	3.24	4.50	2.10			0.905 NS
MV (m^3 tree^{-1})	30	26.19	54.04	6.32	0.944^{***}	3.14	0.78 (58)
UV (m^3 tree^{-1})	30	23.62	52.43	3.64			0.440 NS
MH (m)	30	3.15	4.32	2.08	0.940^{***}	0.157	−0.54 (58)
UH (m)	30	3.23	4.50	2.10			0.593 NS
UVR1 (m^3 tree^{-1})	376	22.68	58.16	0.33	0.892^{***}	2.70	−0.34 (750)
UVR2 (m^3 tree^{-1})	376	22.89	52.82	0.50			0.731 NS
UHR1 (m)	376	3.23	4.50	0.90	0.874^{***}	0.169	−0.35 (750)
UHR2 (m)	376	3.24	4.50	0.90			0.724 NS

measurements was high for both tree height ($R^2 = 0.996^{***}$; RMSE = 0.0397 m) and volume ($R^2 = 0.995^{***}$; RMSE = 0.868 m^3). Non-significance of the *t*-tests indicated that there was no bias in the manual measurements between different days (Table 1).

The repeatability of ultrasonic measurements, estimated by comparing two independent measurements of the 30 trees on different days, was also high (tree height $R^2 = 0.929^{***}$; RMSE = 0.170 m, and volume $R^2 = 0.945^{***}$; RMSE = 3.14 m^3). Non-significance of the *t*-tests indicated that there was no bias in the ultrasonic measurements between different days (Table 1; Figs. 6 and 7). Although the repeatability of ultrasonic measurement was lower than manual measurement, the ultrasonic repeatability of both height and volume measurements was best with smaller trees, as indicated by the reduced scatter of points in the lower portions of the regressions (Figs. 6 and 7).

Accuracy of the ultrasonic measurements relative to manual reference measurements on these 30 trees was also high (tree height $R^2 = 0.940^{***}$; RMSE = 0.157 m, and volume $R^2 = 0.944^{***}$; RMSE = 3.14 m^3). These volume accuracy data were similar to those reported by Whitney et al. (2002) for smaller trees (RMSE = 1.67–2.64 m^3 tree^{-1}). Statistics for goodness of fit for the regressions were similar for repeatability and accuracy (Table 1). *t*-tests indicated no significant bias in ultrasonically measured tree height and volume accuracy, but the level of significance was lower than in the tests of repeatability (Table 1). The slight bias can be seen in the scatter plots (Figs. 8 and 9), where ultrasonic heights were over-estimated, and ultrasonic volumes were under-estimated. These biases were probably

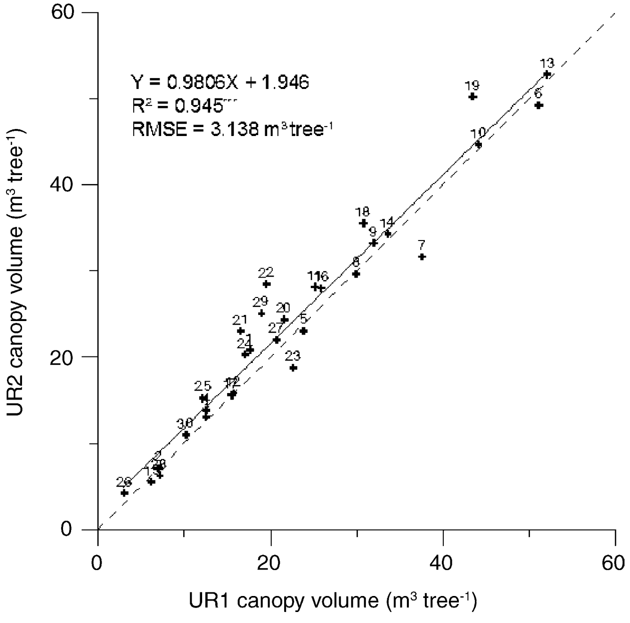

Fig. 6. Regression between canopy volumes of 30 selected trees measured by the ultrasonic system on two consecutive days (R1, R2). The broken line represents a 1:1 relationship.

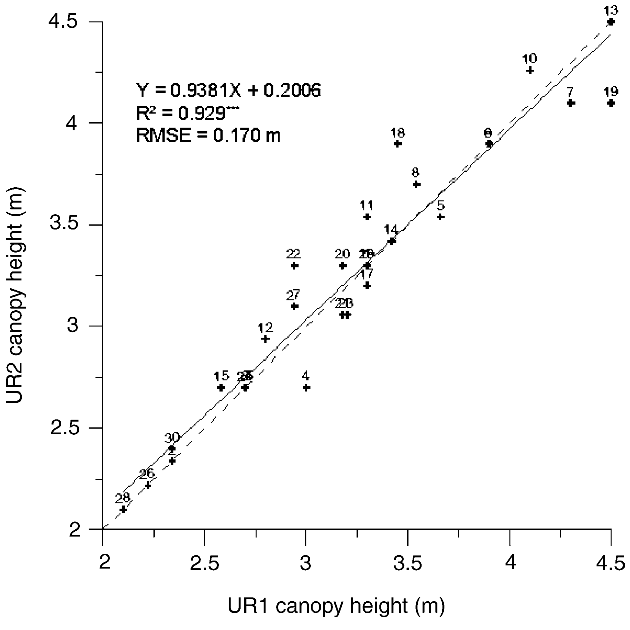

Fig. 7. Regression between canopy heights of 30 selected trees measured by the ultrasonic system on two consecutive days (R1, R2). The broken line represents a 1:1 relationship.

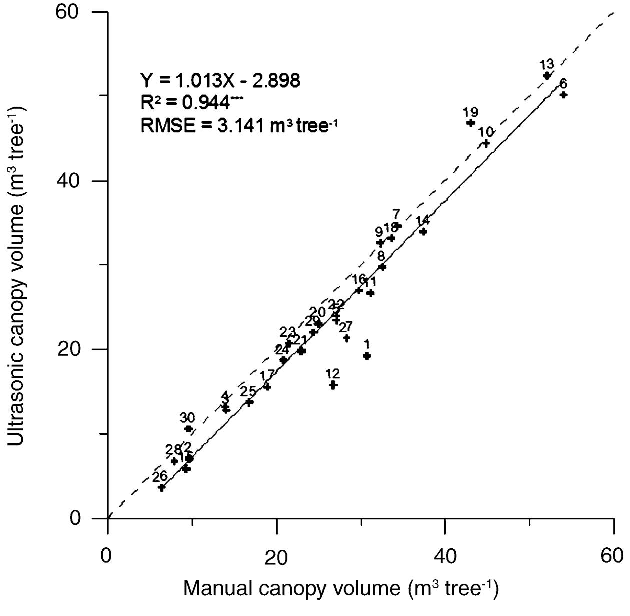

Fig. 8. Regression between canopy volumes of 30 selected trees measured manually and by the ultrasonic system. The broken line represents a 1:1 relationship.

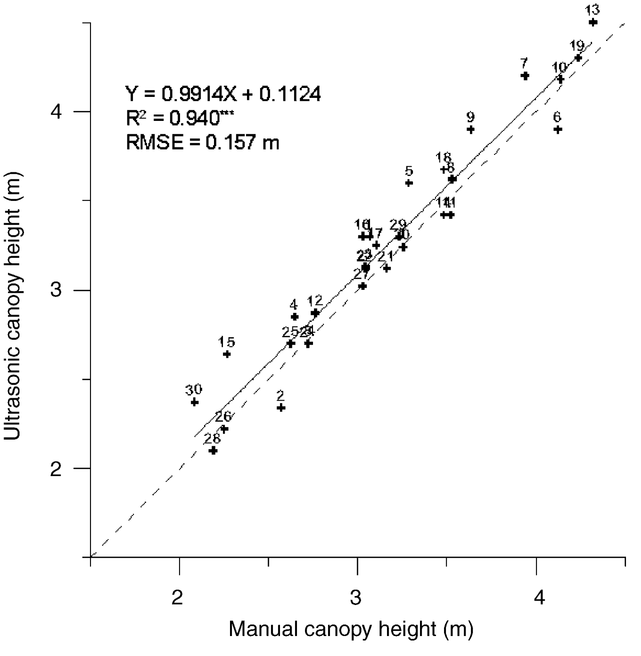

Fig. 9. Regression between canopy heights of 30 selected trees measured manually and by the ultrasonic system. The broken line represents a 1:1 relationship.

from cumulative error terms inherent in the ultrasonic system, some of which are listed below:

- ultrasonic ranging measurement error due to uncalibrated air temperature;
- error in speed and position measured by DGPS;
- error due to dynamic vehicle orientation affected by pitch, roll, and yaw;
- height errors in the transducer array due to tire inflation, soil penetration, wheel tracks, and uneven ground;
- error from vehicle and transducers not being perfectly centered between tree rows;
- error due to tree asymmetry, not accounted for in computation of canopy volume from one half of the tree;
- error due to ultrasonic beam divergence;
- error due to eight-bit analog to digital conversion of transducer data (7.6/255 m);
- error from signal sensitivity loss caused by ultrasonic wavefront lagging behind due to forward speed of vehicle.

The repeatability of ultrasonic measurements with all 376 test trees was similar to that with 30 trees (Table 1; tree height $R^2 = 0.874^{***}$; RMSE = 0.169 m, and volume $R^2 = 0.892^{***}$; RMSE = 2.70 m^3). The slightly lower coefficients of determination could be due to the much greater degrees of freedom for the full data set ($n = 376$), compared to the selected subset ($n = 30$). Non-significant *t*-tests for the comparison of ultrasonic replicates (Table 1) indicated that these measurements were unbiased, as shown in Figs. 10 and 11.

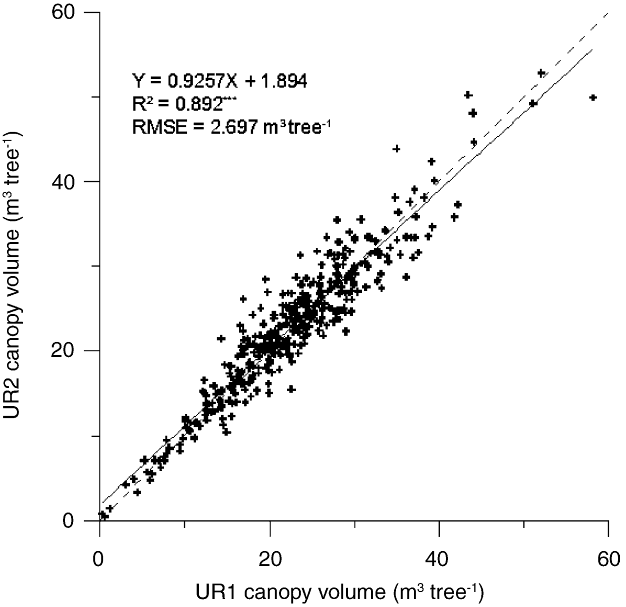

Fig. 10. Regression between canopy volumes of 376 trees measured by the ultrasonic system on two consecutive days (R1, R2). The broken line represents a 1:1 relationship.

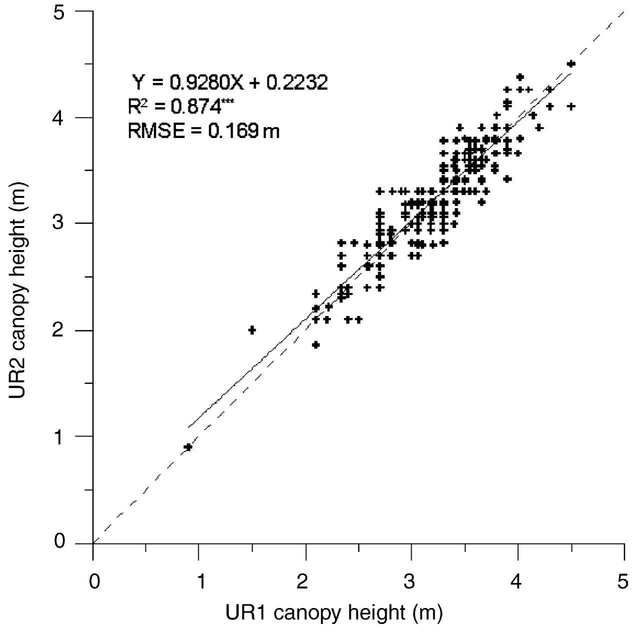

Fig. 11. Regression between canopy heights of 376 trees measured by the ultrasonic system on two consecutive days (R1, R2). The broken line represents a 1:1 relationship.

Table 2
Differences in tree position location (R1 − R2) measured independently on 2 days by DGPS and ultrasonic system for 376 trees

n	Mean (m)	Median (m)	Minimum (m)	Maximum (m)	95-percentile (m)
376	0.69	0.64	0.03	2.12	1.37

The 376 tree positions located by the DGPS and custom software on different days had a mean repeatability error of 0.69 m, with a range of 0.03–2.12 m. On average, the error in tree location was less than 1.37 m, 95% of the time (Table 2). These position errors were similar to the specifications of the Trimble AgGPS 132 (<0.5 m dynamic horizontal accuracy; $0.044\,m\,s^{-1}$ speed accuracy), but were magnified by some of the additional interacting errors listed above.

4. Conclusion

The Durand-Wayland 10-transducer ultrasonic array and custom software proved very efficient at measuring tree canopy height and volume at an actual rate of about 13.6 trees per minute in this grove. Theoretical measurement rate was 14.5 trees per minute, but excluded time taken to turn between rows. By upgrading to a dual array of 10 transducers measuring two rows of trees simultaneously, the measurement rate could easily be doubled to 30 trees per minute. Although the transducer firing rate is limited by the speed of sound in air, and careful synchronization with offset timing is needed between neighboring transducers to avoid interference, it should be possible to refine the ultrasonic array's performance to achieve faster ground speeds and greater measurement rates. Manual measurements would typically take more than a minute per tree.

The ultrasonic system was sufficiently accurate and repeatable for many site-specific or precision agriculture uses. Applications of the system could include the real-time determination of tree canopy sizes for yield estimation, variable rate fertilization or pesticide spraying, or the production of accurate grove inventories and maps to track every tree in the grove on a GIS.

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References

Durand-Wayland Inc., 1998. Smart spray operator's manual. LaGrange, GA.

Giles, D.K., Delwiche, M.J., Dodd, R.B., 1988. Electronic measurement of tree canopy volume. Trans. ASAE 31 (1), 264–272.

Hodges, A., Philippakos, E., Mulkey, D., Spreen, T., Muraro, R., 2001. Economic impact of Florida's citrus industry, 1999–2000. Economic Information Report 01-2, University of Florida, Gainesville, FL.

Kataoka, K., Okamoto, H., Kaneko, T., Hata, S., 2002. Performance of crop height sensing using ultrasonic sensor and laser beam sensor. ASAE Paper No. 021184. St. Joseph, MI, ASAE.

Li, B., Whitney, J.D., Miller, W.M., Wheaton, T.A., 2002. Ultrasonic-based canopy volume measurements of citrus trees for precision agriculture. ASAE Paper No. 02-021053. St. Joseph, MI, ASAE.

Roper, B.E., 1988. Grove sprayer. Winter Haven, FL, U.S. Patent No. 4768713.

Solanelles, F., Planas, S., Escola, A., Rosell, J.R., 2002. Spray application efficiency of an electronic system for proportional application to the canopy volume. Aspects Appl. Biol. 66, 139–146.

Tumbo, S.D., Salyani, M., Whitney, J.D., Wheaton, T.A., Miller, W.M., 2002. Investigation of laser and ultrasonic ranging sensors for measurement of citrus canopy volume. Appl. Eng. Agric. 18 (3), 367–372.

Wheaton, T.A., Whitney, J.D., Castle, W.S., Muraro, R.P., Browning, H.W., Tucker, D.P.H., 1995. Citrus Scion and rootstock, topping height, and tree spacing affect tree size, yield, fruit quality, and economic return. J. Am. Soc. Hort. Sci. 120 (5), 861–870.

Whitney, J.D., Tumbo, S.D., Miller, W.M., Wheaton, T.A., 2002. Comparison between ultrasonic and manual measurements of citrus tree canopies. ASAE Paper No. 021052. St. Joseph, MI, ASAE.

Zaman, Q.U., Salyani, M., 2004. Effects of foliage density and ground speed on ultrasonic measurements of tree volume. Appl. Eng. Agric. 20 (2), 173–178.